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A methodological approach to assess the hazard of underground cavities subjected to environmental weathering

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A R T I C L E I N F O

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A B S T R A C T

Soft highly porous carbonate rocks, such as calcarenites, and soluble sulphate rocks, such as gypsum, are very common in the Mediterranean region and, due to their microstructure and chemical composition, are prone to water induced weathering mechanisms. Cliffs, underground cavities and other morphological features in such formations are hence affected by intense erosion phenomena and weathering processes responsible for unexpected collapses and sinkholes. Just considering the Apulian region (Italy), 150 sinkholes have been recorded since 1925, with increasing frequency since 2000 (Fiore et al., 2018). The geosystem's failure is often the short- or long-term result of a very complex hydro-chemo-mechanical process taking place at the micro-scale which can be detected and analysed by means of field and laboratory experimental test campaigns. Therefore, stability problems are often related to changes of the mechanical properties of the rock forming the cave caused by environmental weathering processes, despite the external boundary conditions are not changing with time. The paper deals with the assessment of hazard associated with the stability of abandoned underground caves, which is nowadays frequently required for land and urban planning activities. A methodological approach for hazard assessment based on a step-by-step procedure is proposed. This includes in-situ surveys, laboratory experimental studies, theoretical analyses and finally numerical investigations. The approach derives from the experience developed from several case studies analysed by the authors. In this work, two of these are presented. The first one concerns the stability of an anthropic cavity in a calcarenite formation which is affected by a water induced short-term and long-term debonding processes. The second one regards the stability of a three-level abandoned gypsum mine, the lowest level being partially flooded by water. The methodological procedure aims to evaluate the factors controlling the change of the mechanical properties of the rock so that efficient remediation measures can be designed in order to avoid any further decay of the rock mass stability with time.

The proposed methodological approach, validated on real case studies, shows the convenience of performing advanced experimental, theoretical and numerical studies to properly assess the hazard in space and time and to better design the mitigation measures if they are required. The adoption of the proposed approach reduced the remediation costs of the second case study of one order of magnitude.

1. Introduction

The assessment of hazard associated with the stability of man-made underground caves, which were exploited and abandoned some decades ago, is still nowadays frequently underestimated during land and urban planning activities. This is generally related to the loss of historical memory concerning the existence of old underground caves in land management processes, as well as the change of the boundary conditions working on the cave systems that leads to the consequent variation of the rock material properties over time, even in a relatively short time. High-risk conditions are also enhanced by the fast development of urban areas, which gives frequently rise to the existence of buildings and infrastructures lying over caves that cannot be considered safe. Recent case studies of collapse of man-made underground caves, with consequent sinkholes affecting urbanized areas, are well described in the literature, as for example those involving the calcarenite caves in Southern Italy (Parise and Lollino, 2011; Vattano et al., 2013; Fiore et al., 2018), the metal mining caves in Canada (Bètournay, 2009), the siltstone Longyou caverns in China (Li et al., 2009; Yang et al., 2011) and the limestone mines in the Netherlands and Belgium (Bekendam,

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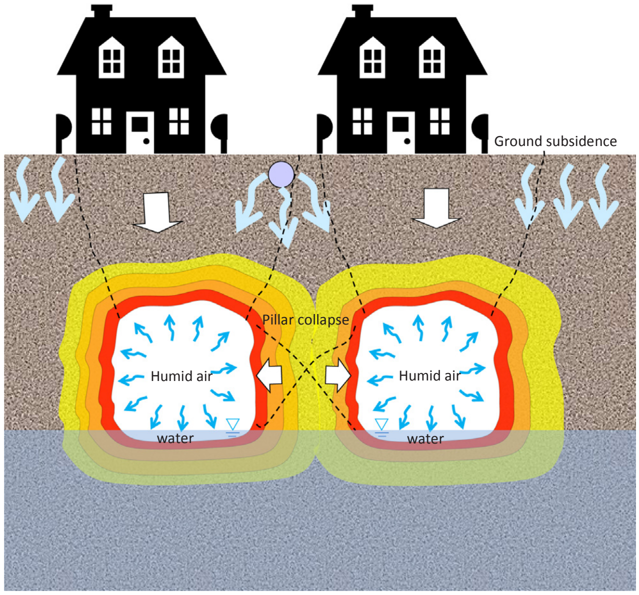

Fig. 1. Environmental weathering and cave instability.

1998; Van Den Eeckhaut et al., 2007).

Instability of caves is frequently associated with the occurrence of degradation of the mechanical properties of the rock surrounding the cave as a consequence of environmental processes. In particular, water infiltration from the ground surface or pipe leakage, the increment of relative humidity of the cave environment, as well as more extreme cave flooding are all related to the increment of the degree of saturation of the rock over time and the consequent rock degradation (Fig. 1). This is particularly true for those rocks that are highly sensitive to the interaction with water, as for example evaporitic rocks and soft porous rocks. Several studies have been proposed on this subject, as for example those concerning the iron ore abandoned mines in Lorraine, as discussed in Grgic et al. (2006), the aging of gypsum in underground mines (Auvray et al., 2004, Castellanza et al., 2010) and the works on the debonding processes affecting the calcarenite outcropping in Southern Italy (Andriani and Walsh, 2007; Ciantia and Hueckel, 2013; Ciantia et al., 2014, 2015).

The methods for the assessment of the stability of underground caves that are available in the scientific literature can be generally classified according to three classes: phenomenological, analytical and numerical approaches. Phenomenological methods are generally based on abaci that show areas representing stable or unstable cave configurations on the basis of geometrical parameters of the cave and strength parameters of the rock, as derived from a large number of case studies (Potvin and Milne, 1992; Nickson, 1992; Carter, 1992; Goodings and Abdulla, 2002). Analytical closed-form solutions have been instead widely used to calculate elastic solutions for roofs with very simple geometries, such as caves with circular or rectangular shape (Obert and Duvall, 1967; Jaeger and Cook, 1969), followed by closed form solutions accounting for the elasto-plastic behaviour of the rock material (Lippmann, 1971; Ribacchi and Riccioni, 1977; Brown et al., 1983; Detournay and Fairhurst, 1987; Panet, 1995; Carranza-Torres and Fairhurst, 1999; Gesualdo et al., 2001; Diederichs and Kaiser 1999).

Recently, numerical modelling has provided a powerful tool to explore the stress-strain state within the rock mass around the cavities and the corresponding displacement field induced by a specific loading condition or a change of the boundary conditions, also adopting advanced non-linear constitutive models. To mention a few, Mortazavi et al. (2009) propose a numerical investigation of the failure mechanism of rock pillars in underground openings by taking into account the effect of pillar geometry and pillar strength parameters for typical situations existing in the Canadian mines. Bekendam (1998) studied the stability of calcarenite and limestone mine pillars in the Netherlands by means of two-dimensional elasto-plastic finite element (FE) models, also implementing time-dependent creep processes, whereas Parise and Lollino (2011) highlighted with the same 2D FE approach the role of the degradation processes of the limestone and calcarenite rock surrounding caves in Southern Italy in the development of sinkholes. Ferrero et al. (2010) detect the areas of highest stress concentration and calculate the corresponding safety factors of the most loaded pillars by means of a 3D FE analysis of old underground calcareous quarries in the Western Alps (Italy). Ghabezloo and Pouya (2006) perform FE analyses aimed at studying roof stability of limestone caves in France due to tensile strength degradation induced by karst processes. Diederichs (2003) investigates rock fracture mechanisms and global collapse of caves by means of the distinct element method, whereas Wang et al. (2011) explore the failure mechanisms of underground cave pillars by means of the application of the Rock Fracture Propagation Analysis. From a theoretical point of view, a well-consolidated experience has been gathered in the numerical application of simple elasto-plastic constitutive models, such as those implementing the Mohr-Coulomb (MC) or the Hoek-Brown (HB) failure criterion (Pelizza et al., 2000; Zhang et al., 2016; Fazio et al., 2017; Jiang et al., 2017). Trinh and Jonsson (2013) developed an elasto-plastic finite element model of an underground cavern room in hard rocks, also accounting for the effects of reinforced bolts. On the other hand, more advanced constitutive models have been recently implemented in numerical codes to simulate the variation of the rock mechanical properties due to environmental factors and the coupled chemo-mechanical processes associated (Fernandez-Merodo et al., 2007; Grgic et al., 2006; Ciantia and Castellanza, 2016; Tamagnini and Ciantia, 2016).

Based on the aforementioned technological development, the paper aims to propose a procedure of hazard assessment for underground caves, based on the experience and the theoretical research developed by the Authors in some recent case histories. In particular, a methodological approach based on in-situ surveys (including the use of Laser-Scan techniques to define model geometry), laboratory and field investigations, theoretical and numerical analyses is presented in the following. Two case studies are discussed within the framework of the procedure proposed and some conclusions regarding the evolution of the cave stability over time are drawn accordingly.

2. Methodological approach

The proposed methodological approach for the quantitative assessment of failure susceptibility associated with the presence of underground caves follows a procedure formed of six steps (Fig. 2):

(1) *In-situ survey*: preliminary field surveys should be carried out both inside the caves and at the ground surface according to either conventional topographical survey methods or advanced tools, as laser-scan techniques, in order to define a three-dimensional geometrical model of the overall area; then, a detailed geological and hydro-geological analysis should follow to define the lithological model, the geo-structural setting and the eventual existence of hydro-geological features, as water circulation or infiltration from ground surface;
(2) *Choice of the conceptual model*: this second stage should be aimed at defining the general features of the real problem's schematization and is represented by the choice between a 2D or a 3D model geometry (based on the eventual existence of plane-strain conditions), as well as the choice between a continuum or a discontinuum model, according to the eventual existence of relevant joints;
(3) *Experimental analysis*: this step is finalized at defining the factors that play a major role in the stability of the rock mass around the cave, as current mechanical properties of the involved material, susceptibility of the rock to weathering and degradation processes,

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